Chapter 1

Introduction

The study about the history of our universe is one of the most captivating areas of study in the present day. After the Big Bang nucleosynthesis, the universe was filled with ionized plasma. As the universe started to cool down, the protons and electrons that were present started to recombine rapidly, becoming neutral and releasing the Cosmic Microwave Background (CMB). The time during which the electrons and protons were combined for the first time which lead to the formation of hydrogen atoms is known as recombination epoch and can be probed well by the Cosmic Microwave Background Radiation (CMBR). Soon after the epoch of recombination, the universe entered into the "dark age", a phase where no consequential source of radiation was present. The hydrogen that was present in the universe, remained neutral during this epoch. The detailed observations of the CMBR established a concept that the large scale structures that are present in the current Universe stem due to the small amplitude density fluctuations. Due to the gravitational instabilities, the inhomogeneities in the dark matter density field that were present during the recombination epoch started growing, which gave rise to highly nonlinear structures like the collapsed halos.

These halos of matter started accumulating more and more baryons due to their gravitational pull and finally started to form the first sources of light in the Universe. In the study of the universe, one of the lesser know period is the Epoch of Reionization. The photons produced by these first stars, quasars reionized the neutral Hydrogen (HI) present in the intergalactic medium (IGM). This transition of the Universe from neutral to ionized is referred to as the Epoch of Reionization (EoR), which is still mostly an unobserved enigma.

The Epoch of Reionization, lasted for about a billion years between the CMB last scattering surface at redshift $z \sim 1100$ and the complete ionization of hydrogen in the intergalactic medium (IGM) by z ~ 6. At present the understanding of this epoch is limited to the observations of cosmic microwave background radiation (CMBR) and high redshift quasar absorption spectra. These types of indirect observations are restricted in providing valuable information regarding the EoR. The ionization history during this particular era was dependent on the properties of the first stars and galaxies. This era and the physics govorning this period thus have extensive importance in understanding the structure formation in the Universe. There are substantial challenges in observing the Universe at such early times. Our universe is made of 4% baryons, in that 4%, 75% is hydrogen and 25% is Helium. The most abundant element in the Universe is hydrogen and one of the possible ways to understand the EoR is by observing the radiation emitted from the neutral hydrogen (HI). The spin flip hyperfine transition emitted from the hydrogen atom has a rest frame wavelength of ~21 cm.

The intensity or brightness temperature of the redshifted 21 cm line coming from very early universe is our best bet to probe the distribution of HI from the EoR. Observing the line will help us to study the entire history of reionization as it progresses with redshift. A large number of experiments are underway to measure the redshifted 21-cm signal from the early Universe utilizing low-frequency radio interferometers like the GMRT , LOFAR , MWA , PAPER , 21CMA . These are the first generation radio telescopes, thus they are just sensitive enough to detect and characterize the signal by means of statistical estimators . Because the sensitivity of the first generation interferometers is relatively low, thus they are not capable of specifically imaging the HI distribution. The advent of extremely sensitive next-generation telescopes such as the SKA will help us to gain more information about the HI distribution by actually making 3D tomographic images of the HI distribution across cosmic time.

However, before generating the images from these observations that will be available in future, one needs to understand, what kind of signal one is looking for and has to come up with various methods to interpret the observed signal. This implies that one would need to consider all possible physically plausible models for the EoR. To achieve this, the EoR community has developed various simulations to predict the possible 21 cm signal, considering different models for the sources and also the physics that goes on in the IGM. These simulations are of various kinds, one where the physics is precisely taken into consideration, i.e. full radiative transfer simulations, in which one can follow the path of each individual photons while they move through the IGM. These types of simulation are computationally challenging and expensive. The taxing computing demands do not allow the radiative transfer simulations to simulate cosmologically relevant large volumes if they are trying to mimic the small scale physics. Another way to simulate this era is where the simulation is done approximately, via photon counting using excursion-set-like formalism. These are called semi-numerical simulations and are used widely due to their quick computation time and limited memory requirement. Using these simulations one can explore many models of reionization very quickly. Thus they are and will be very handy when one would need explore a wide variety of reionization models. These approaches are well adapted to obtain the size distribution of the ionized regions for arbitrary models of the luminosity function and the time history of the effectiveness of ionizing photon emission. However, the physical assumptions that are made by these type of simulations are quite drastic and sometimes lead to artifacts and small scale errors in simulating the early Universe. When simulating the reionization scenario, various kinds of possibilities that cause the reionization history and process to vary should be considered possibilities such as the variation of the source model, physics of IGM, variations in the nature of the dark matter etc. Two specific aspects that impact the neutral hydrogen distribution the most is the properties of sources, i.e. the sources that emit ionizing photons, and the properties of dark matter. These two particular aspects can impact the reionization process and its history significantly. How the production rate of ionizing photons from the sources has an impact on reionization or not. What physics in simulation is more important from an observational point of view. Whether recombination of ionized hydrogen will significantly change the observed signal. How the nature of the dark matter can affect the reionization history. All of these aspect need to be studied and understood properly before interpreting the future high definition observations of the EoR using telescopes like the SKA.

That is where the visualization of simulations of this era becomes essential. By visualizing the simulations, the impact of the source model, the impact of physics in the IGM e.g. recombination, the effect of different dark matter models can be understood and quantified. This will help us to understand where the approximations considered in our simulations are acceptable and where they are becoming barrier to distinguish between different reionization scenarios. This will help us to figure out the accuracy that are necessary to mimic the essential physics during this period through our simulations. In this particular thesis, we used visualization of different simulations to study the impact of different reionization scenarios that are plausible realistically. We used visualization techniques to study two specific aspects of reionization through simulations, they are:

- The impact of different kinds of dark matter models and how they affect the structure formation and in turn the reionization history and neutral hydrogen topology.

- The impact of different kinds of source models for the production of ionizing photons on the resulting 21 cm signal and HI topology during the EoR.

Chapter 2

21 cm signal from the Epoch of Reionization

2.1 Hydrogen

The most abundant element in the interstellar medium (ISM) is the hydrogen, and it is also the simplest atom. It comprises a proton and an electron bound together. They are detectable through the λ = 21cm (frequency = 1420.4057 Mhz) hyperfine line.

The redshifted 21 cm hydrogen line is a distinctive and often highly effective probe to research the forming phases of galaxies and clusters of galaxies in the early universe.

2.2 21 cm line

The state n = 1 (ground state) of hydrogen undergoes hyperfine splitting comprising the spins of the proton and the electron. Due to the spin-flip transition of an electron in the ground state of a hydrogen atom, wavelength corresponding to 21 cm or frequency 1420 Mhz is emitted. The parallel spin state (triplet state) has higher energy than the anti-parallel spin state (singlet state). The 21 cm line connected with the spin-flip transition in the hydrogen atom, i.e. from the triplet state to the singlet state is oft-times used to detect neutral hydrogen in the universe .

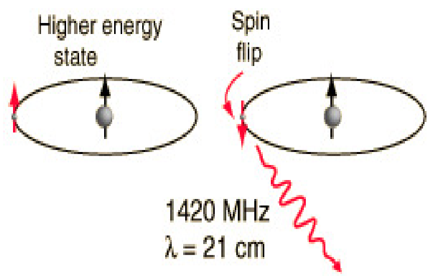

Figure 2.1: The Spin flip transition of electron in the ground state of hydrogen atom,wavelength corresponding to 21cm or frequency 1420 Mhz is emitted.

Harold Ewen and Edward M purcell first discovered this hydrogen line at Harvard in 1951, accompanied shortly afterwards by researchers in Holland and Australia. In 1944, the Dutch astronomer H.C van de Hulst observed that the 21 cm line would be detectable in emission.

The underlying physics of the hydrogen spin transition is as follows. The hyperfine levels of ground-state of hydrogen appear to thermalize with the CMB. This will make the IGM unobservable. The gas becomes observable against CMB either in emission or absorption only if a process, shift the hyperfine level populations away from thermal equilibrium. The relative population of the spin levels is usually described in terms of the hydrogen spin temperature T_S, as defined by

$$\frac{n_1}{n_0} = 3exp\left\{\frac{-T_*}{T_s}\right\} \tag{2.1}$$

n_0 and n_1 refers to the singlet state and triplet state of hydrogen atom. $T_\star$ = 0.068 K is described by kB$T_\star$ = E_{21}, which is 21 cm transition energy and $E_{21} = 5.9 \times 10^{-6}$ eV, which corresponds to a photon frequency of 1,420 MHz.

It is possible to observe the IGM only when the kinetic temperature T_k of the gas (due to the motion of its atoms) differs from CMB temperature T_{CMB}, and an effective mechanism couples T_s to T_k. In early times, collisions influenced this coupling owning to high gas density. Once there was a wide number of galaxies in the Universe, the spin temperature was influenced by an indirect process, i.e. scattering by Lyman-α photons. This effect is called the Wouthuysen-Field effect. It is named after the Dutch physicist Siegfried Wouthuysen and Harvard astrophysicist George Field. In this process an atom, which is initially in the state, n = 1 absorbs a Ly-α photon, and goes through a spontaneous decay that returns it from the state n = 2 to the state n = 1. This would result in a final spin condition that is distinct from the original one .

At an observing wavelength of $21(1+z)$ cm, the optical depth produced by a patch of neutral hydrogen at the mean density and with a uniform spin temperature T_s (after correcting for stimulated emission) is

$$\tau(z) = 1.1 * 10^{-2}\left(\frac{T_{CMB}}{T_s}\right)\left(\frac{1+z}{10}\right)^{1/2} \tag{2.2}$$

here, $z \gg 1$.

The spectral intensity I_ν is observed relative to the CMB at a frequency ν by radio astronomers as an effective brightness temperature T_b of black-body emission at this frequency. This is defined using the Rayleigh-Jeans limit of the Planck formula,

$$I_\nu = \frac{2K_B T_b \nu^2}{c^2} \tag{2.3}$$

The brightness temperature through the IGM is,

$$T_{CMB}e^{-\tau} + T_s(1 - e^{-\tau}) \tag{2.4}$$

Then the observed differential temperature of this region relative to the CMB is given by,

$$T_b = (1+z)^{-1}(T_s - T_{CMB})(1 - e^{-\tau}) \tag{2.5}$$

$$\simeq (29\, mK)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{T_s - T_{CMB}}{T_s}\right) \tag{2.6}$$

where $\tau \ll 1$ and T_b is redshifted to z = 0.

The observed T_b in over dense region is proportional to the overdensity and T_b is proportional to neutral fraction in partial ionized region. If $T_s \gg T_{CMB}$, then the IGM is observed emission and if $T_s \ll T_{CMB}$ then the IGM is observed in absorption.